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Manufacturing Methods and Technology

EVALUATION OF ISOTHERMAL FORGINGS FOR T53 IMPELLERS

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The primary objective of this program was to evaluate isothermal forgings of Ti-6Al-4V alloy in the form of near-net shaped T53 impellers and determine their potential technical and economic advantages over conventional forgings. An evaluation of mechanical properties showed the isothermal forging properties to meet current forging specifications. Finish machining of one forging was conducted using the current production process. This revealed a time saving of 2.1 standard hours over the

20. ABSTRACT - (Continued)

conventional forging, a savings primarily in rough machining. Partially formed vanes are not realized as an advantage by the current milling process due to the cam controlled action of the cutter in the existing machining facility, i. e. several Gorton milling machines.

A cost analysis of alternative vane milling methods, i. e. numerical and/ or adaptive control, has led to the conclusion that a process modification would not be cost effective due to current high efficiency of the Gorton mill. It is therefore recommended that a partial vane contour be included in the forged shape only to the extent that it is effective in reducing input material cost without increasing forging costs.

FOREWORD

This project was accomplished as part of the U. S. Army Manufacturing Technology program. The primary objective of this program is to develop, on a timely basis, manufacturing processes, techniques, and equipment for use in production of Army Materiel.

This final technical report was prepared by Avco Lycoming Division, Stratford Connecticut for the Army Materials and Mechanics Research Center, Watertown, Massachusetts under Contract No. DAAG-75-C-0078; program monitor for AMMRC was Mr. E. Kinas. The period of program activity was from 16 June 1975 through 16 December 1975.

Avco Lycoming personnel who participated in this program included Mr. G. Scarich, Mechanical Testing; Mr. V. Strautman, Experimental Machining; and Mr. E. Zadeh and Mr. D. Carroll, Cost Analysis, Mrs. E. Knauf acted as Project Engineer and Mr. L. Fiedler was Program Manager.

Comments are solicited on the potential utilization of the information contained herein as applied to present and/or future production programs. Such comments would be sent to: U. S. Army Aviation Systems Command, Attention: DRSAV-EXT, P. O. Box 209, St. Louis, Mo. 63166.

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1.0 INTRODUCTION

Advanced fabrication techniques have received increased attention because of their potential to reduce the costs of turbine engine components. Isothermal forging is such a technique; its primary advantage is the ability to produce a near-net shape and thereby improve material utilization. A program to investigate the potential of isothermal forging to produce a Ti-6Al-4V alloy impeller for the T53 has been completed by IITRI under sponsorship by AMMRC (1), the program objective being to produce an impeller forging requiring a minimum of machining. In the IITRI program, several forgings with partial vane channels were produced. This forging, shown in Figure 1, weighs 22.5 lbs compared to the conventional forging weight of 37.5 lbs and the finished part weight of 11.45 lbs. Isothermal forging in this case has reduced the amount of metal to be removed by nominally 50 percent.

The purpose of this program was to further evaluate the isothermal forgings from the IITRI program, to investigate their quality, determine critical mechanical properties, and assess the cost savings potential of the near net shape forging by machining a finished component using existing facilities. In addition, cost savings were projected for the machining of an isothermal forging using optimized facilities, e.g. advanced numerical control machining techniques.

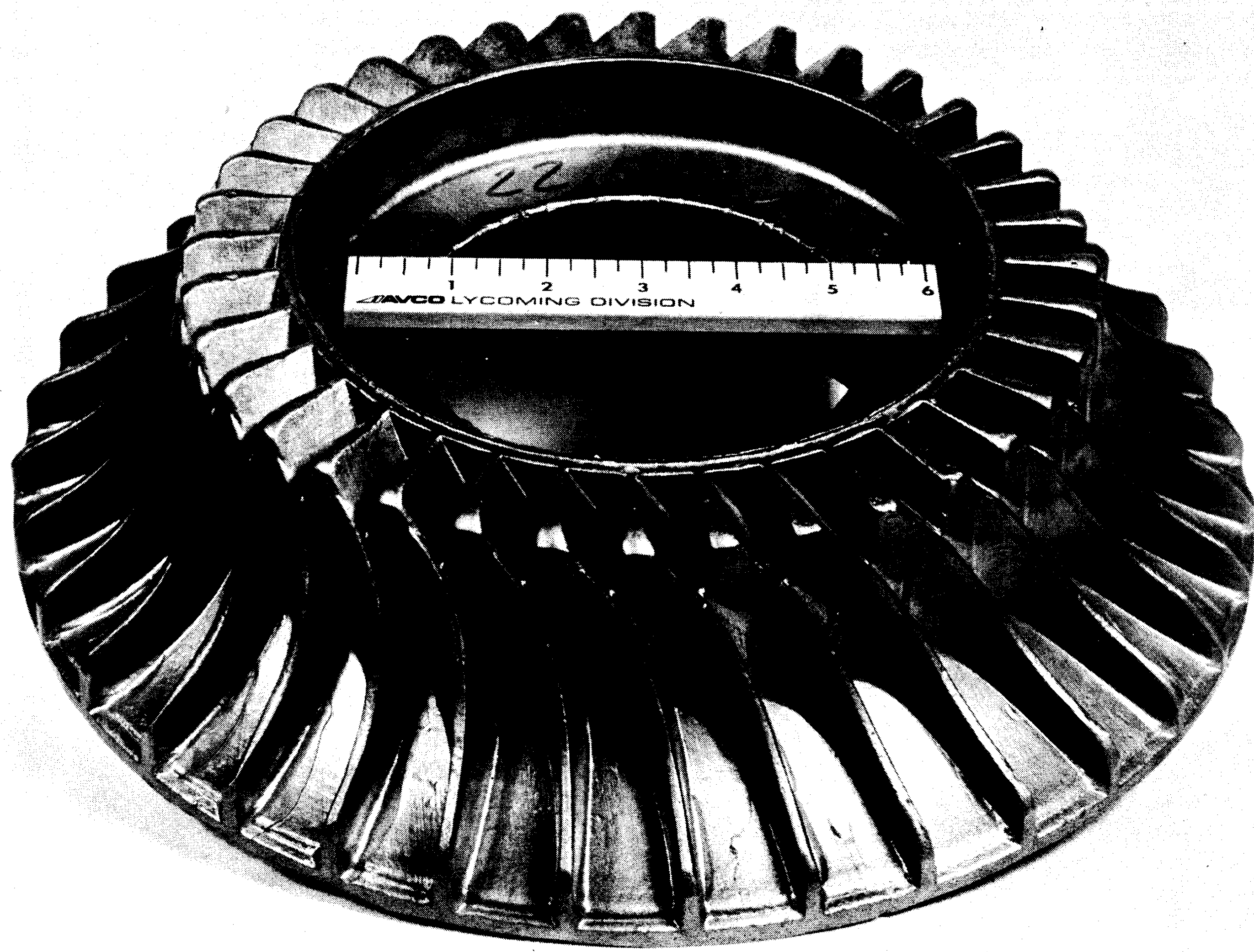


Figure 1 T53 Impeller Forging S/N 6 as Isothermally Forged by IITRI

2.0 DESCRIPTION OF PROGRAM

The forgings as supplied by the Army Mechanics and Materials Research Center (AMMRC) were first evaluated non-destructively. This evaluation included visual and fluorescent penetrant checks for surface flaws, and an ultrasonic inspection for internal defects within limitations imposed by the shape of the forging. The forging judged most sound was dimensionally inspected to ascertain if sufficient material stock existed for a finish machined part. A metallographic evaluation and chemical analysis were conducted on one forging designated for cut-up.

Tensile and notch rupture tests were conducted on one forging in accordance with Lycoming Specification M3403, the specification for Ti-6Al-4V in the solution treated plus aged condition. Low cycle fatigue (LCF) and high cycle fatigue (HCF) properties were also evaluated as these properties are generally limiting factors in an impeller's design and service life.

A finish machined forging was produced to evaluate the forgings cost reduction potential. This machining utilized the current production process whenever possible. The operations were monitored to determine applicability to an optimized production procedure and to reveal any unforseen machining problems associated with the forging configuration. This information as well as projections on the effects of advanced machining techniques were considered in the final cost analysis. A flow diagram of the program is given in Figure 2, and a detailed description of the program is given in the following paragraphs.

2.1 Test Material

Three forgings were sent to Avco Lycoming by AMMRC. These forgings had been solution treated at 1750°F (954°C) for one hour and water quenched, then aged at 1100°F (593°C) for four hours and air cooled. This aging treatment differed from M3403 which calls for an age of 1000°F (538°C) for eight hours after solution treating. The effects of this deviation on test results, will be discussed in the next section. Each forging was weighed to determine the effect of preform size on defects and fill.

2.2 NDE

The visual inspection was conducted to determine the presence of laps, pits, lack of fill or cracks which were sufficiently severe to reject the piece as unsuitable for finish machining. Fluorescent penetrant inspection was used to confirm the presence of defects observed visually. The amount of penetrant bleed-out was used as an indication of defect severity.

Forging S/N 10 was used to investigate the ultrasonic inspectability of the isothermal near net shape. Figure 3 shows three locations in which No. 3 flat-bottom holes (3/64 inch) were drilled in this part. All three forgings were hand scanned in an ultrasonic immersion tank using a 10 MH_z transducer (1/4" diameter) with a 1 inch focal length.

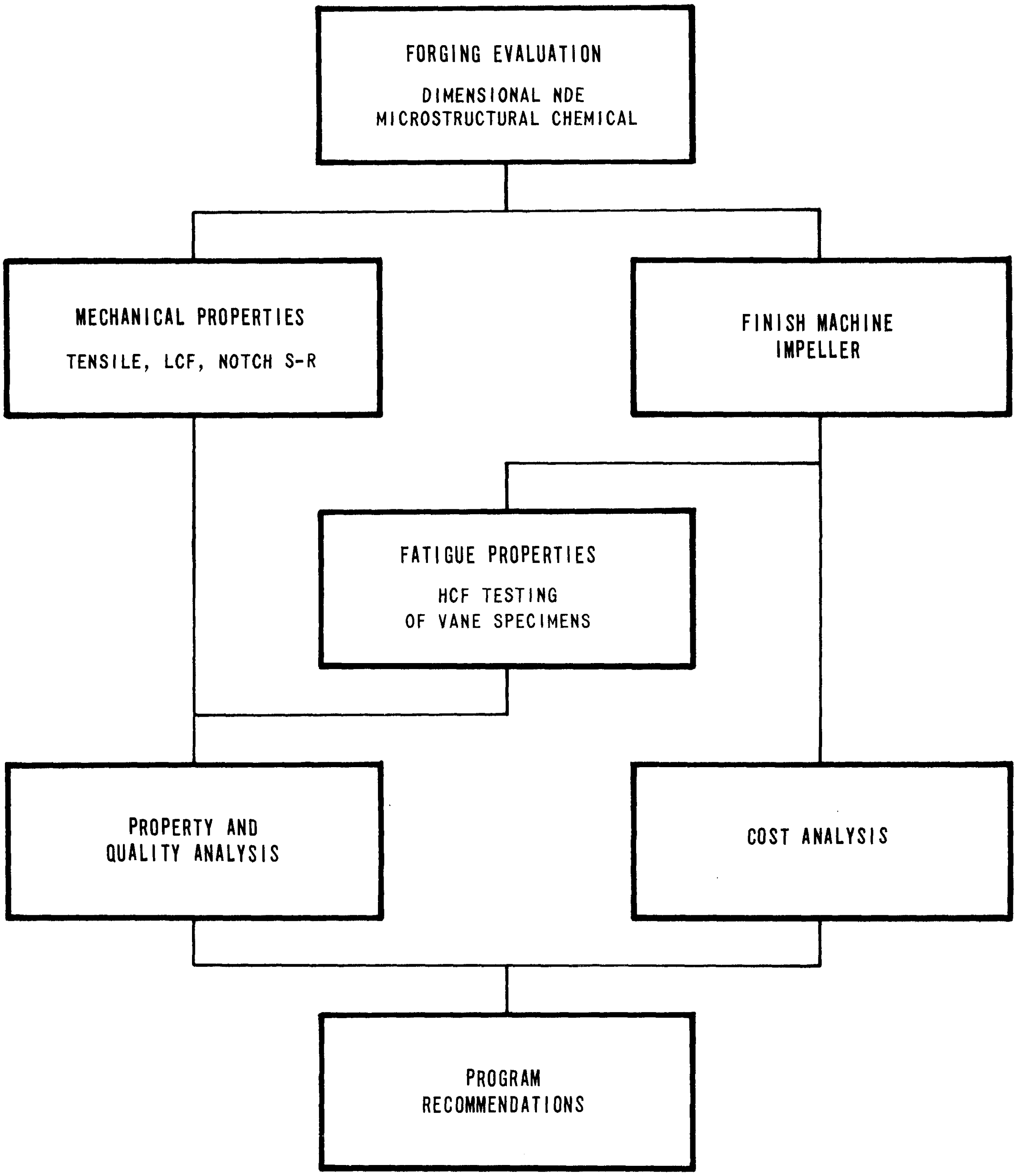


Figure 2 Program Outline

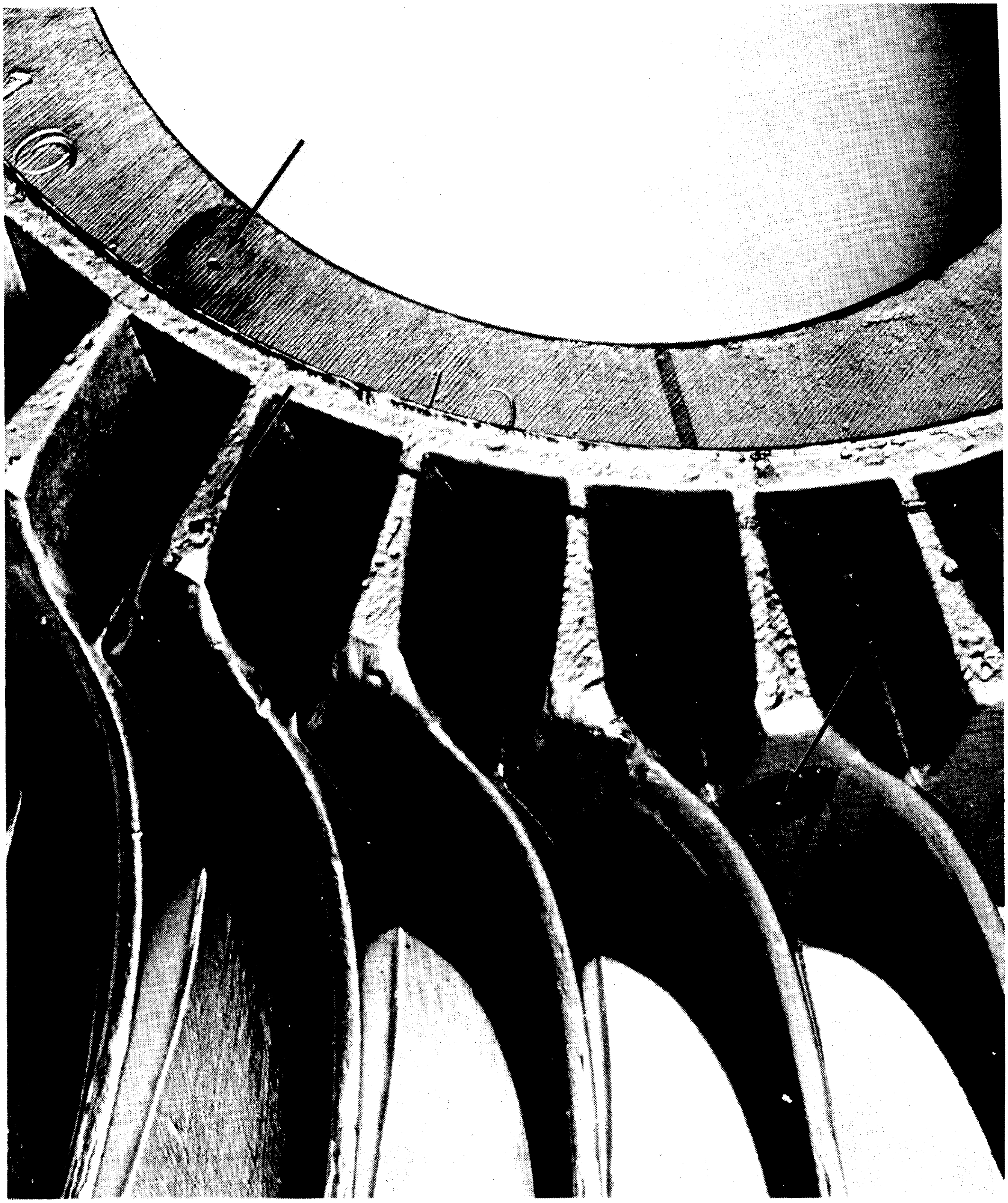


Figure 3 Location of Ultrasonic Test Holes in Forging S/N 10

The forging which appeared most likely to produce a finished impeller was dimensionally checked to determine if it possessed a sufficient material envelope for all surfaces to clean up and meet the finish drawing dimensions.

2.3 Metallurgical Evaluation

Metallographic and chemical analysis were conducted on forging S/N 10 to determine conformance to M3403. This forging showed the poorest fill and was designated as the cut-up part for metallurgical and mechanical property investigations. General microstructure was determined by optical microscopy and flow lines by an etched cross section. Alpha case and alpha segregation were additionally evaluated by means of a polished cross section using an anodic etching technique. Chemical analyses were conducted using atomic absorption for metallic elements, Leco analyzers for hydrogen, oxygen and carbon, and the Kjeldahl distillation method for nitrogen.

2.4 Mechanical Properties

Tensile specimens were machined from various locations in the forging. These were tested at room temperature, as required by M3403, and at 500°F (260°C), the temperature the impeller typically experiences in engine operation. These 500°F tests were conducted in order to compare isothermal properties with conventional forging properties at operating metal temperature. Notch rupture specimens, with a configuration as specified by AMS 4967 (specimen 4), were tested at 185,000 psi (1276 MPa) and room temperature for five hours. Having successfully complied with this requirement, the specimens were then tensile tested to determine their notch-tensile strength.

Strain controlled low-cycle fatigue specimens with radial orientation were tested using an MTS closed loop servo controlled hydraulic test facility. Axial loading was used and longitudinal strain was measured and controlled by means of a remote LVDT located outside the furnace. Tests were conducted at 500°F with $K_t = 1.0$ and $A_\epsilon = 1.0$. Data obtained from these tests was compared with existing data obtained from conventional forged material. The details of this specimen are shown in Figure 4.

High cycle fatigue tests were conducted on vane sections removed from a partially machined forging (S/N 5). Cylindrical plugs were trepanned by EDM after vane contours were machined. Figure 5 shows a sketch of this specimen and Figure 6 illustrates a finished HCF specimen secured in its fixture and ready for test. All specimens were strain gaged to verify the alternating stress. The HCF tests were conducted at room temperature in a modified Budd Model VSP-150 plate bending fatigue tester at 33 Hz.

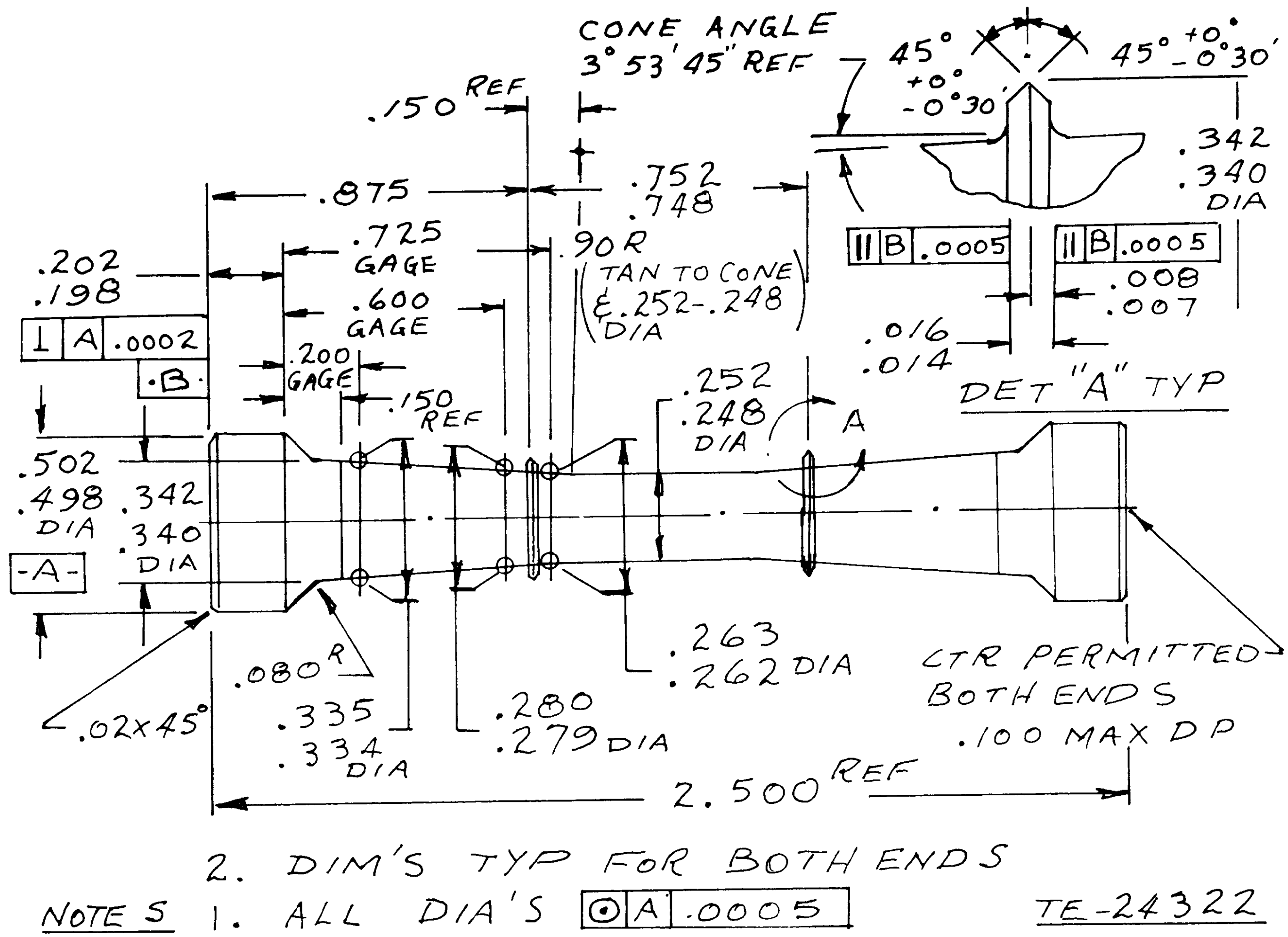


Figure 4. Drawing of Low Cycle Fatigue Specimen

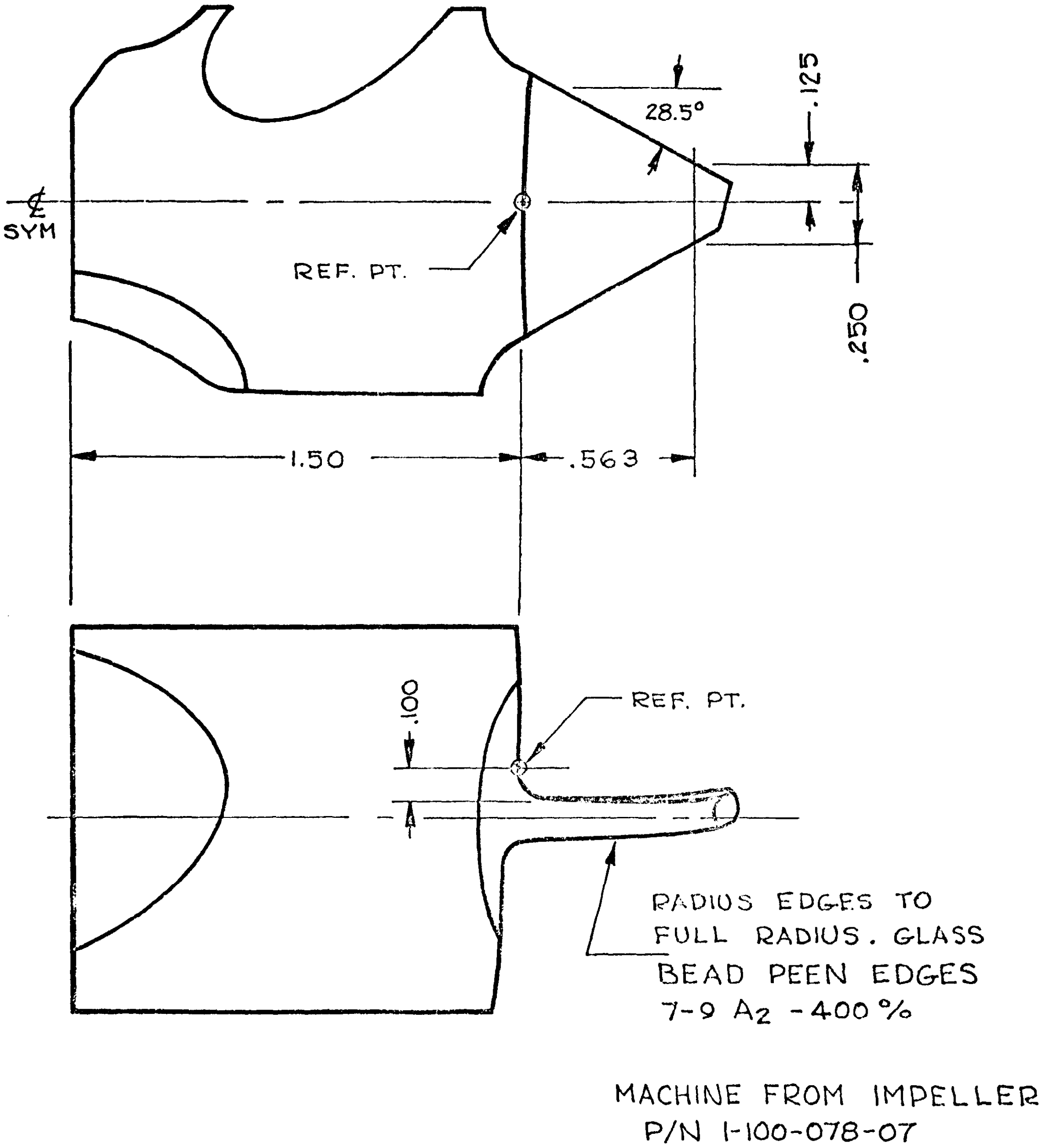


Figure 5. Sketch of High Cycle Fatigue Specimen

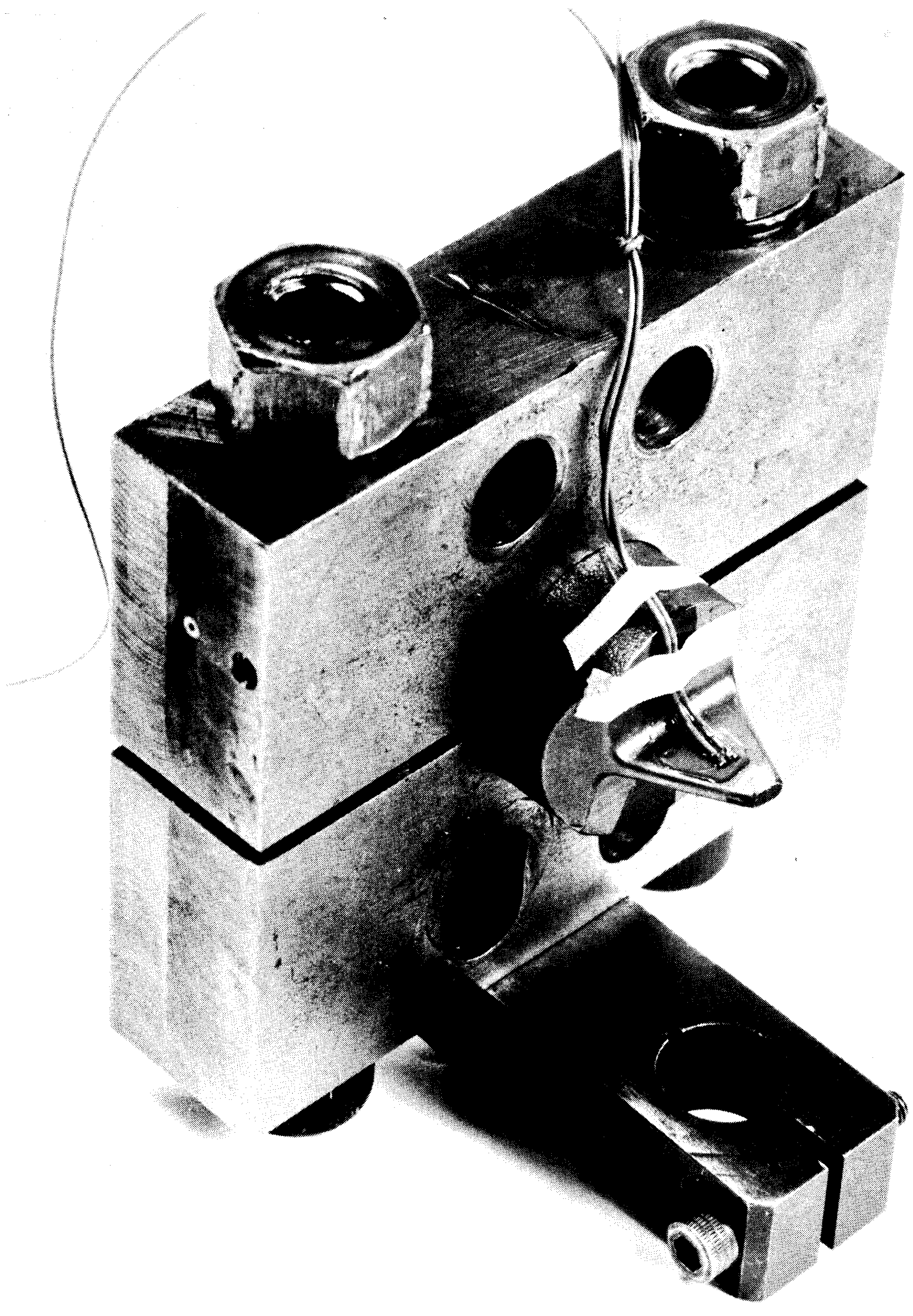


Figure 6. High Cycle Fatigue Specimen in Fixture

2.5 Machined Impeller

A revised process was prepared for the experimental machining of an isothermal forging (S/N 6). The revised process eliminated initial rough machining and turning operations, and added one operation for locating the partially forged vanes in the Gorton mill. In this operation the forging was placed in the Gorton and rotated to such a position that milling cuts would align with vane channels, after which a locating hole was drilled.

3.0 DISCUSSION OF RESULTS

3.1 NDE

3.1.1 Visual and Fluorescent Penetrant Inspection

Visual inspection of forging S/N 10 showed laps in the vanes and on the under face shown in Figure 7. Fluorescent penetrant inspection showed these laps to have a significant depth and were not likely to clean-up on machining. This forging was designated for cut-up. Its weight as-received was 24.4 lbs, although its original billet weight was 25.6 lbs and it was restruck once at 25.28 lbs (Reference 1).

Forging S/N 6, the forging shown previously in Figure 1, was found to have a chamfer on the major OD as well as incomplete fill of vanes both top and bottom. In addition, laps were present on the inner bolting flange. Zyglo inspection confirmed these observations; however, lap depth was indicated to be relatively shallow. Although this piece appeared to have sufficient stock for a finish machined impeller, it was initially designated the source for high cycle fatigue test specimens. However, after vane milling this forging was redesignated for finish machining when it proved to have better clean up at the vane inlet than the forging previously designated for finish machining. Its as-received weight was 22.5 lbs and its billet weight was 24.5 lbs.

Forging S/N 5 shows excellent fill of the lower vane as can be seen in Figure 8 and although there existed a lack of fill on the upper vane, it was less severe than on the other two forgings. Zyglo inspection indicated only minor surface laps. Its as-received weight was 25.0 lbs; its billet weight was 25.9 lbs and it was restruck once at 25.01 lbs.

From the above results and the billet size and weight data in Reference 1, it is apparent that billet configuration, specifically the edge chamfer, was the most important factor in obtaining good fill. Forging S/N 6 had the lowest input weight and yet had the best fill.

3.1.2 Dimensional Inspection

The primary purpose of the dimensional inspection was to aid in selecting the forging which would most likely clean-up on machining a finished part. As formal qualification of the IITRI forging tooling was never intended to be a part of this program, only selected dimensions were inspected. The results of this inspection are tabulated in Appendix A for forging S/N 5.

The inspection did reveal an insufficient forging enevelope for the vane tips at both inlet and exit. The rough machined impellers from both S/N 5 and S/N 6 verified this condition. The lack of clean-up at the inlet side of the passage fillet was not predicted during the inspection. The failure to clean-up was attributed to an improper draft angle and an apparent radial variation of certain individual pocket faces from true center.

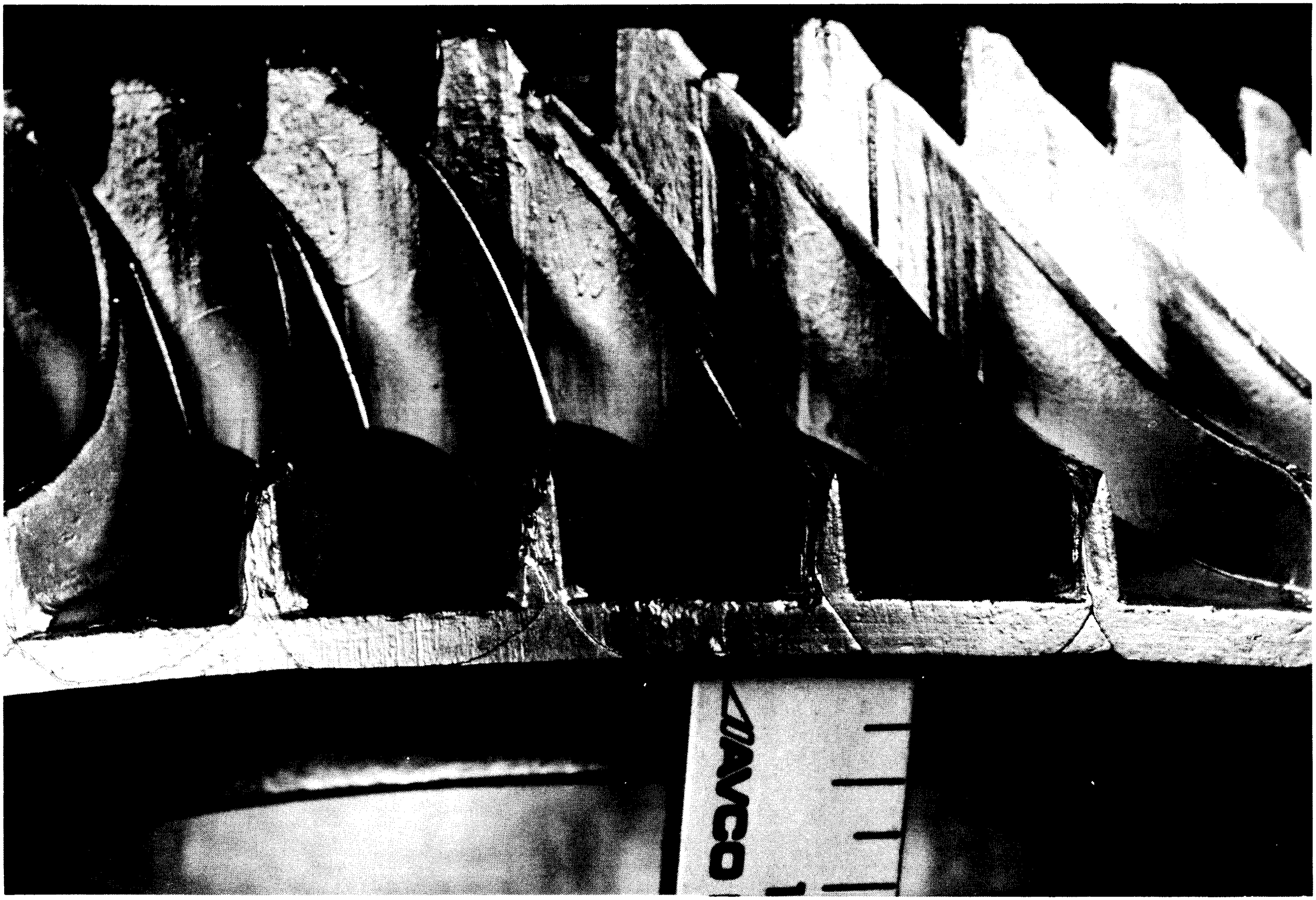


Figure 7. Forging Laps at Periphery of S/N 10

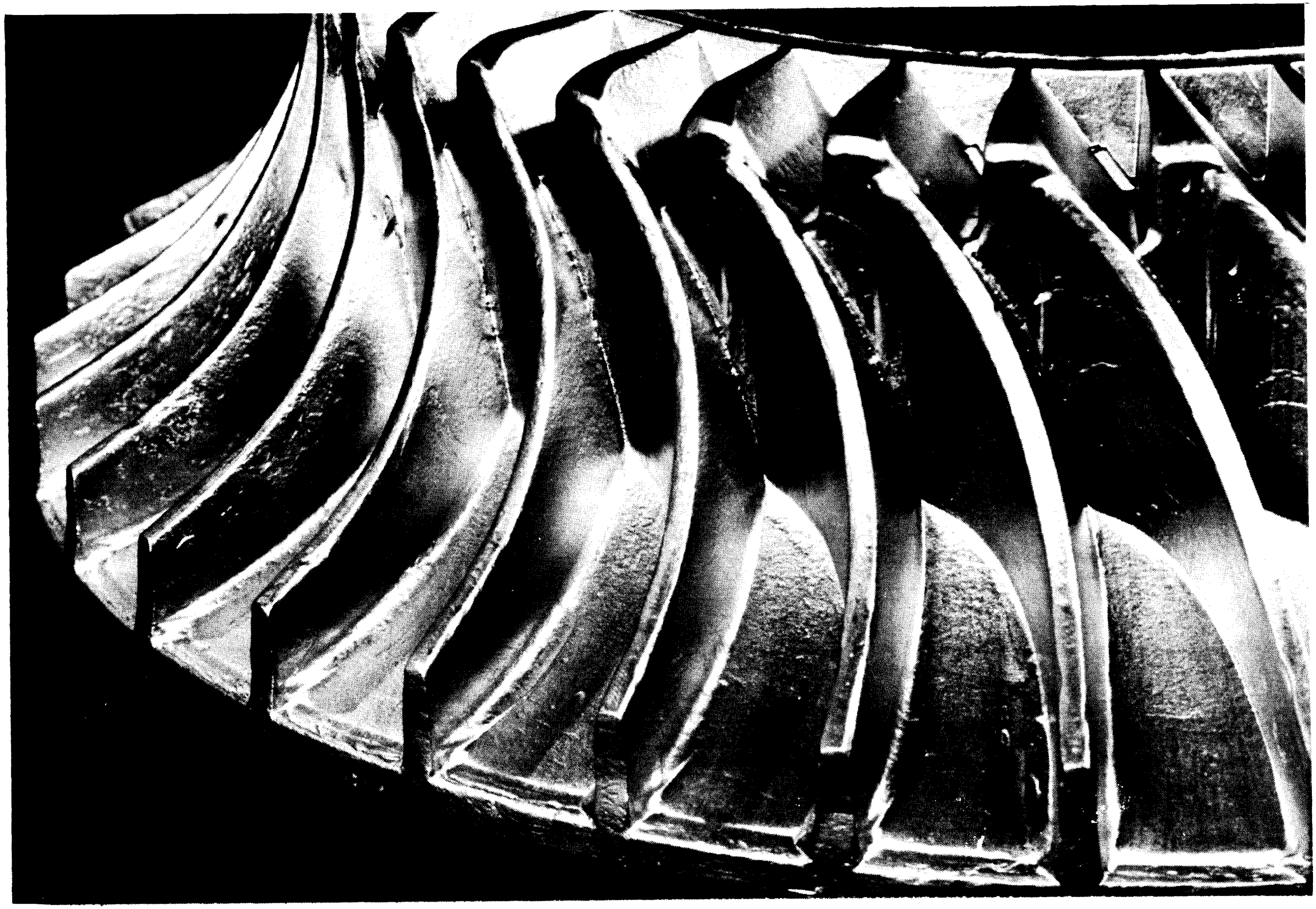


Figure 8. Excellent Fill on Forging S/N 5

3.1.3 Ultrasonic Inspection

The ultrasonic inspectability of any near-net shaped part will likely be compromised if good material utilization is to be achieved. On the isothermally forged impeller, it was demonstrated that approximately 80 percent of the volume could be interrogated in one direction and 30 percent in two directions. This is illustrated in Figure 9 by lines superimposed on a forging cross section. Two views are illustrated so as to aid in visualizing the forging shape.

For purposes of inspecting the forged part, this degree of inspectability is believed to be acceptable for the following reasons:

a) The quality of the forging billet material can be ultrasonically inspected very effectively, that is 100 percent of its volume can be interrogated as round bar stock to at least 3/64 inch defect size.

b) Ultrasonic inspection of the part after forging serves primarily to verify that no defects were generated during the forging operation. The characteristics of the forging operation are such that only surface related defects, such as laps, will be generated by isothermal forging. Defects of this type can be determined most efficiently by Zyglo and visual inspection techniques performed before and after machining.

Further investigation will eventually be required to formulate and verify an NDE plan for a near-net shaped impeller forging. Such an investigation must obviously be conducted on the configuration which is ultimately selected for production.

3.2 Metallurgical Evaluation

A typical macrostructure for the isothermal forging is shown in Figure 10. The longitudinal flow lines in the heavy central section are remnants of billet processing and indicate little upsetting. Flow lines show die extremities were filled uniformly, without flow laps. No evidence of segregation, inclusions, or other abnormal structure could be found.

The forging microstructure, including orientation effects, is shown in Figure 11. It consists of elongated primary alpha in a transformed beta matrix and is acceptable under Avco Lycoming Specification M3403 Microstructure Acceptance Standard - "c". The axis of elongated primary alpha predominately lies along the longitudinal axis, again a billet processing remnant. Presence of primary alpha indicates that temperatures did remain below the beta transus during processing. It was observed that the volume fraction primary alpha increased at the surface to a depth of about 10 mils due to oxygen stabilization. This condition was not sufficiently severe to produce a continuous alpha case, and was not considered detrimental for a part being machined all over.

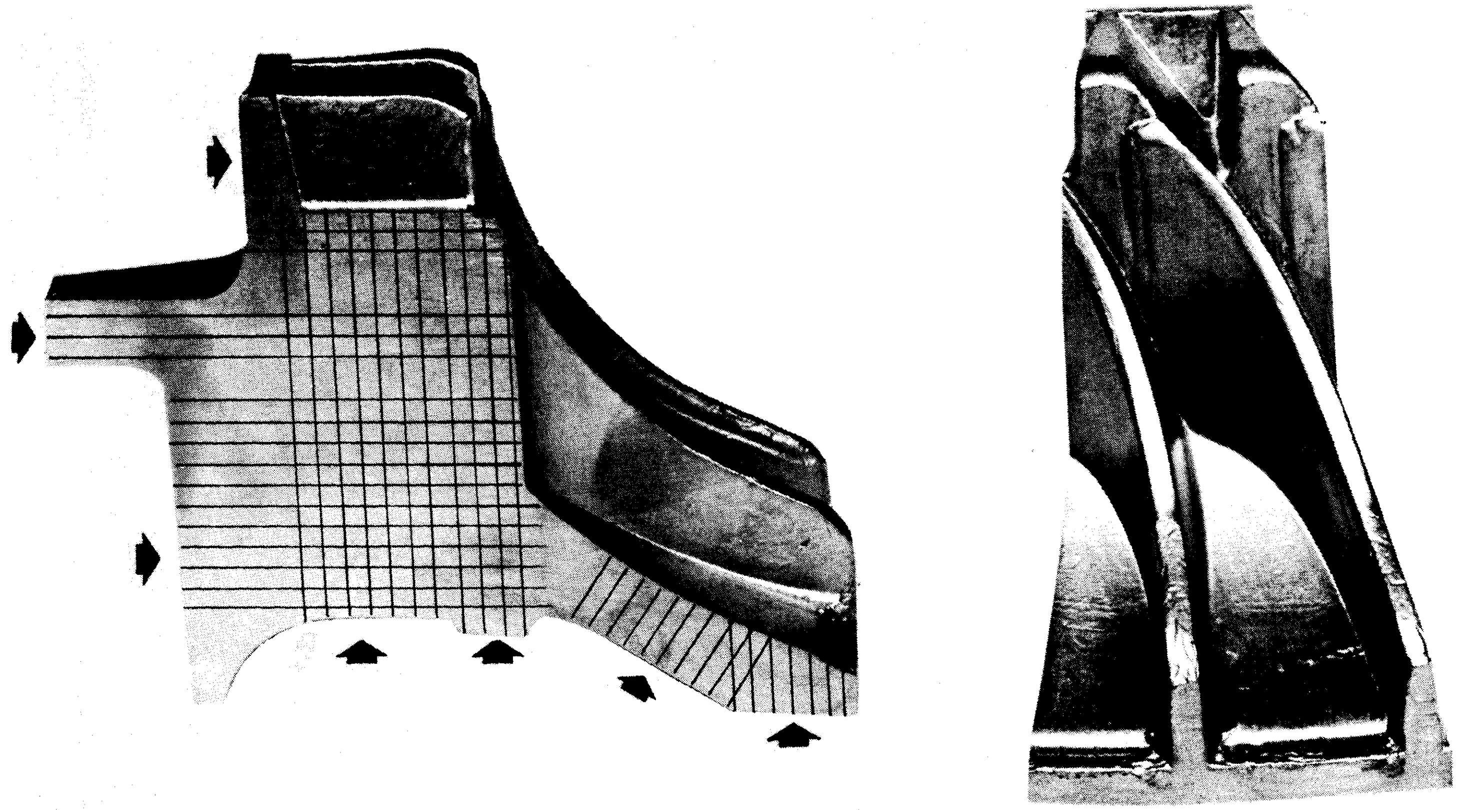


Figure 9. A Forging Section Showing Ultrasonic Inspection Direction and Coverage

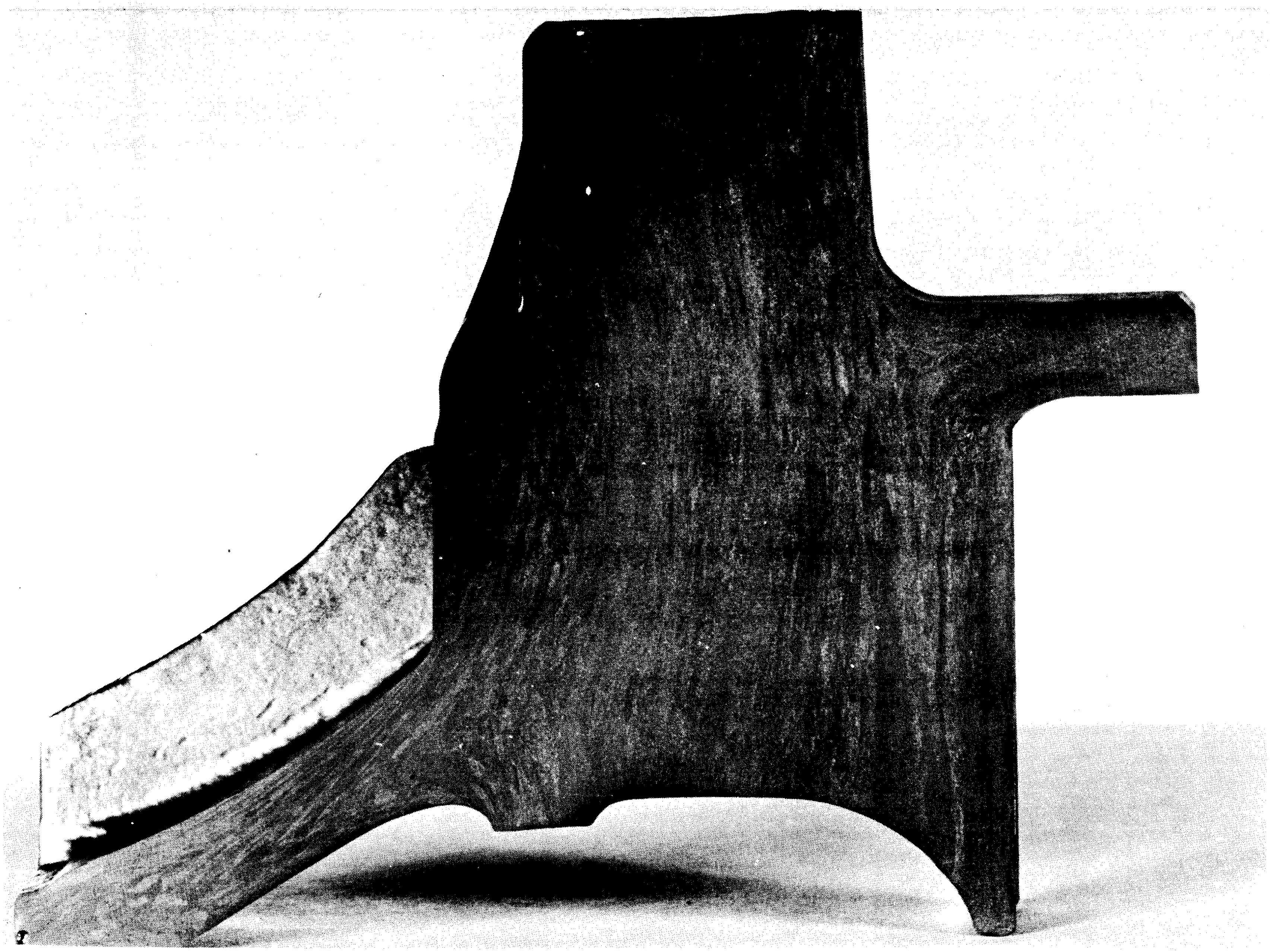


Figure 10. A Macrosection of Forging S/N 10 Showing Flow Lines

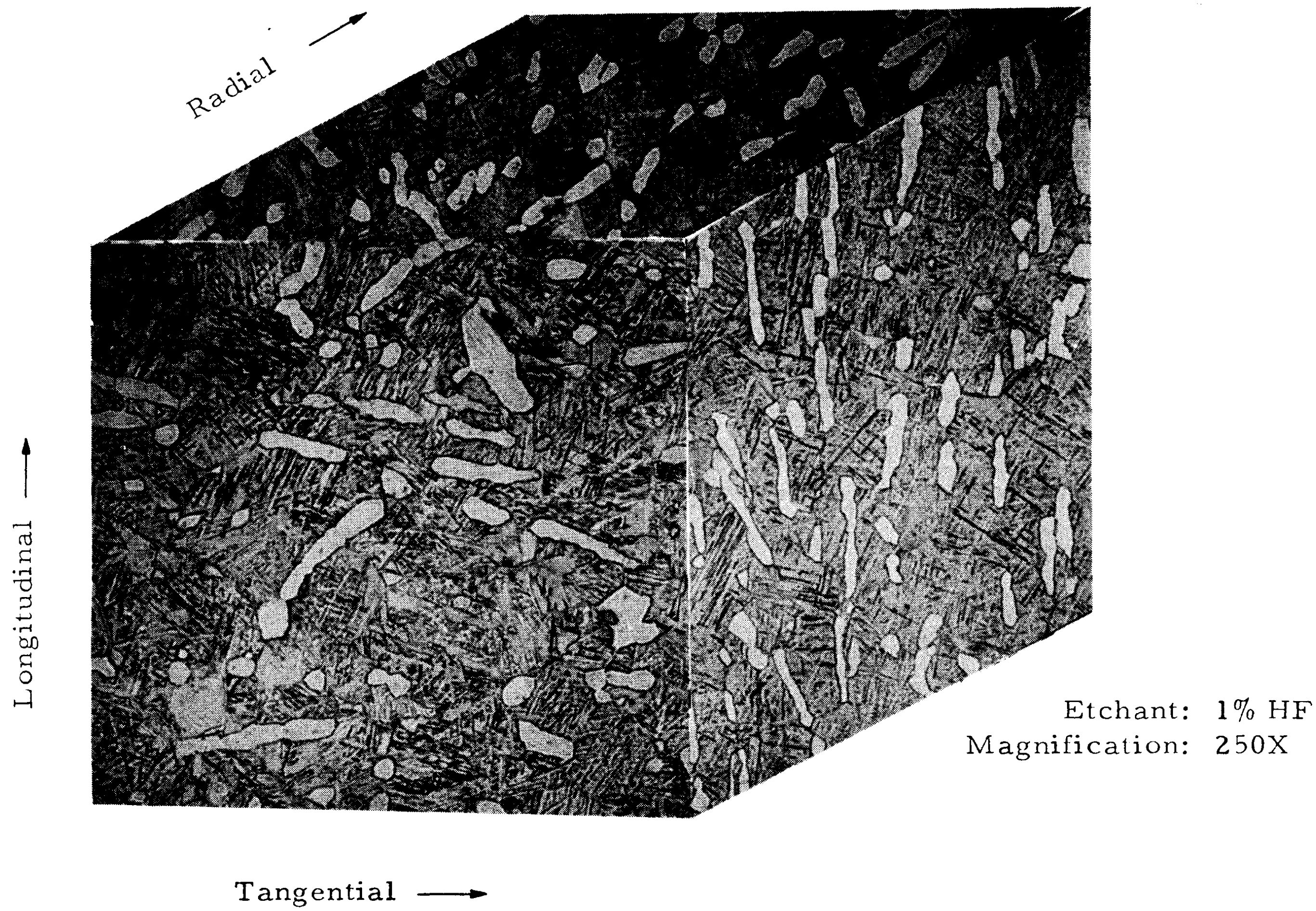


Figure 11. Microstructure of Isothermally Forged Ti6Al-4V Impeller

Results of chemical analysis are shown in Table I. The weight percentages of all elements were found to fall within the ranges specified by M3403.

3.3 Mechanical Properties

3.3.1 Tensile

Tensile tests were conducted at room temperature and 500°F (260°C), with the results shown in Table II. Room temperature results are marginal under M3403 specifications; however, the higher aging temperature used for the isothermal forgings could account for this effect. Elongation and reduction of area results are acceptable.

Tests conducted at 500°F (260°C) also show marginal results with respect to design data for forgings of this cross section. One UTS value and two elongation values are low.

3.3.2 Notch Stress Rupture

Notch rupture specimens were retired after sustaining a load of 185 ksi at room temperature for the required 5 hours. Subsequently a notch tensile test was conducted; specimens failed at the stress levels shown in Table II.

3.3.3 Low Cycle Fatigue

The low cycle fatigue data generated at 500°F (260°C) for forging S/N 10 are given in Table III. Compared with conventionally forged Ti-6Al-4V as shown in Figure 12, the isothermally forged material is equal to or slightly better than the conventional material. These results are considered to be consistent with the strength levels and general microstructure of the isothermally forged material.

3.3.4 High Cycle Fatigue

The high cycle fatigue data generated at 500°F (260°C) for forging S/N 10 are presented in Table IV. Compared with conventionally forged Ti-6Al-4V, as shown in Figure 13, the isothermally forged material revealed a slightly lower endurance limit. However, the endurance limit of forging S/N 10 is considered to be equivalent to that of the conventionally forged material when test scatter is considered.

3.4 Machined Impeller

The primary purpose of machining the impellers was to determine if problems would be encountered in setting up and machining forgings with partial vane passages. Forgings S/N's 5 and 6 were rough machined on the bottom face and the inner bolting flange so that they could be held on the Gorton mill

TABLE I

CHEMICAL ANALYSIS OF ISOTHERMALLY FORGED IMPELLER

Element	Specification Range*	Actual
C	.04 Max	.01
N_2	.05 Max	.02
Al	5.50 - 6.75	6.28
V	3.50 - 4.50	4.03
Fe	.30 Max	.12
H_2	.0125 Max	.008
O2	.12 - .20	.16

*Avco Lycoming Specification M3403

TABLE II

MECHANICAL PROPERTIES OF ISOTHERMALLY FORGED Ti6Al-4V

Test Temperature °F (°C)		Ultimate Tensile Strength psi (MPa)	Yield Strength psi (MPa)		Elongation %	Reduction of Area %
RT		151, 100 (1041.8)	138, 500	(955.0)	11.5	30.0
RT		150, 100 (1034.9)	137, 100	(945.3)	9.9	37.6
RT		152, 550 (1051.8)	140, 600	(969.4)	11.5	33.6
RT		153, 150 (1056.0)	141, 100	(972.9)	13.7	38.6
500 (260)		110, 100 (759.1)	96, 100	(662.6)	13.7	55.8
500 (260)		118, 900 (819.8)	102, 200	(704.7)	15.3	55.6
500 (260)		116, 100 (800.5)	99, 100	(683.3)	15.3	55.4
500 (260)		117, 100 (807.4)	102, 000	(703.3)	14.5	59.2
RT Minimum	△1	150, 000 (1034.3)	137, 000	(944.6)	8.0	20.0
500°F Minimum	△2	116, 000 (799.8)	96, 000	(661.9)	15.0	25.0

△1 Required per M3404 and TQS 30023D
△2 Design Minimum

Notch Stress Rupture at 185, 000 psi (1276 MPa) and RT Hours
5.5 (retired)
5.5 (retired)

Notch Tensile at RT after S-R Test psi (MPa)	
217, 000	(1496.2)
225, 300	(1553.4)

TABLE III

LOW CYCLE FATIGUE DATA

Test No.	Total Strain Range - Percent	Life - Cycles
191	1.0	9,760
192	0.8	25,894
195	0.7	114,503 Retired
198	0.75	58,457
199	1.5	1,530
200	0.09	16,570
201	0.08	52,262
203	1.2	5,040

Note: Forging S/N 10
Test Temperature - 500° F (260° C)

TABLE IV

HIGH CYCLE FATIGUE DATA

Test No.	Maximum Stress ksi (MPa)	Life - Cycles
G1	102.8 (708.8)	464,900
G3	85.0 (586.1)	1,578,100
G2	74.6 (514.4)	2,210,000
G7	72.9 (502.6)	17,270,000
G5	71.4 (492.3)	13,087,900
G4	67.8 (467.5)	14,937,900
G6	63.8 (439.9)	36,061,000 (Retired)

Note: Forging S/N 10
Test Temperature - 500°F (260°C)

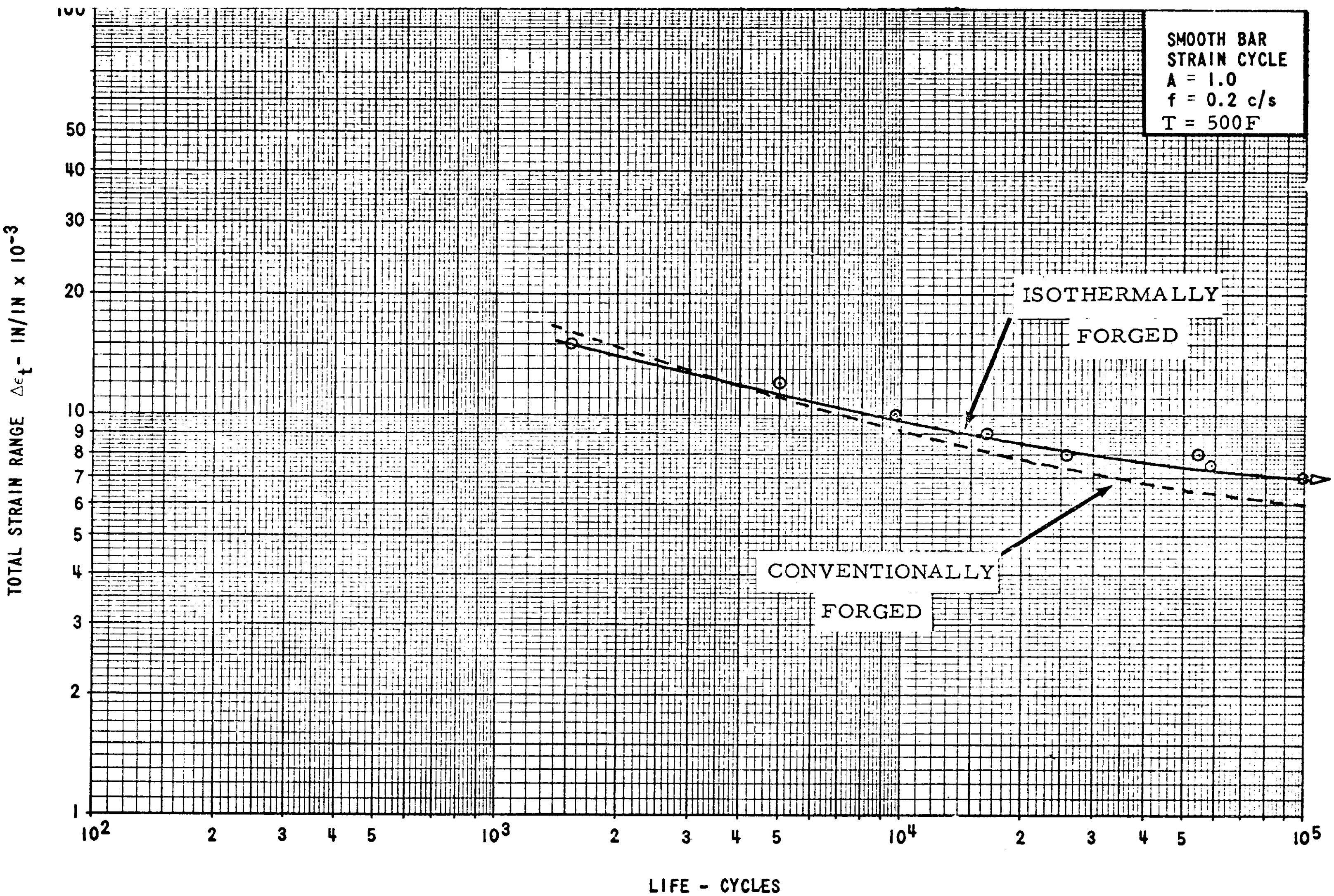


Figure 12. Typical Low Cycle Fatigue Data for Conventional and Isothermal Forged Ti6Al-4V

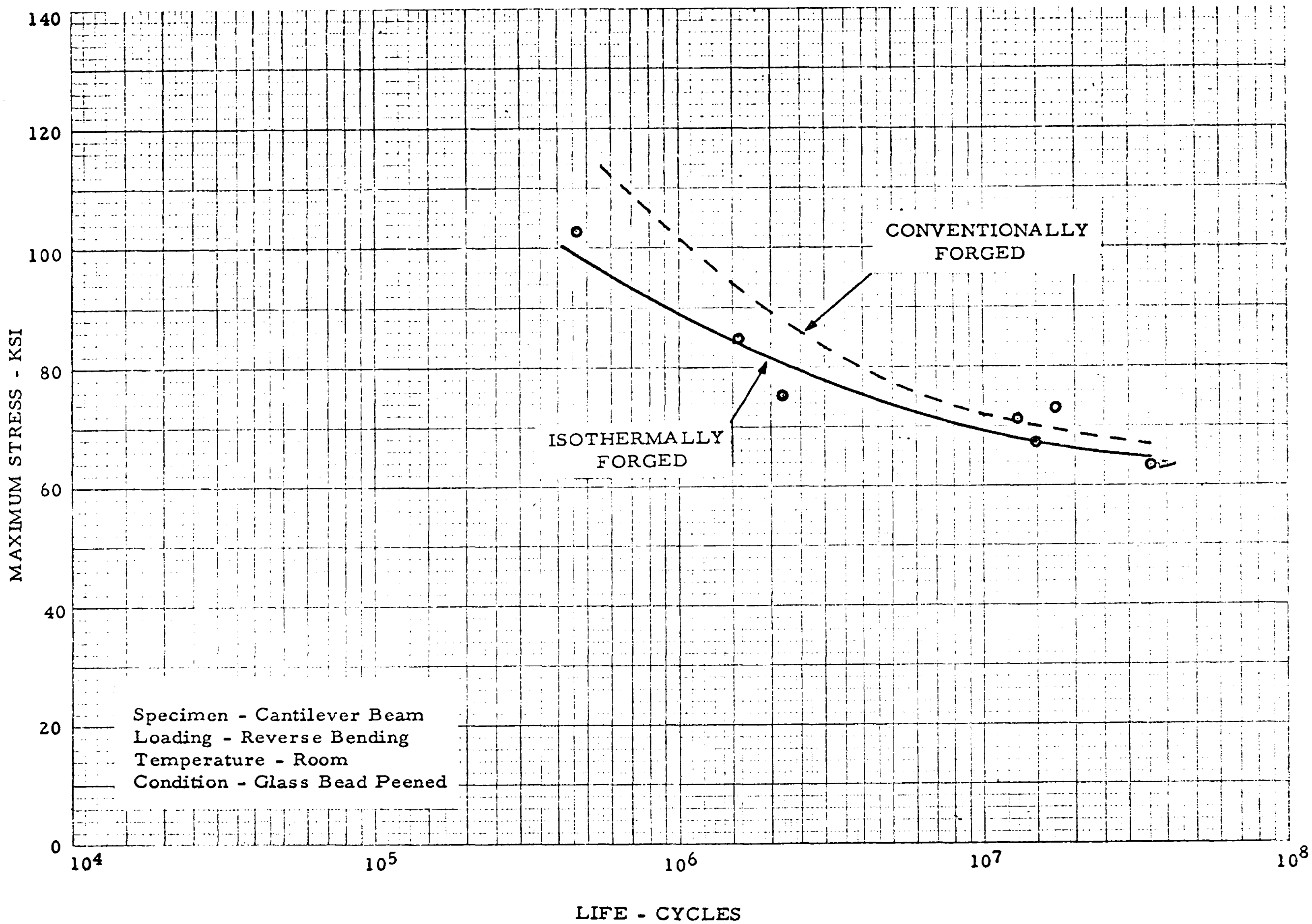


Figure 13. Typical High Cycle Fatigue Data for Conventional and Isothermal Forged Ti6Al-4V

using existing fixturing. Because some of the normal bolting holes are used to hold the part during vane machining, one extra operation had to be added to locate and drill these holes so as to properly index the partially forged vane passages with the mill cutter.

An impeller which has just completed vane machining is shown mounted in a Gorton mill in Figure 14. Each impeller receives two complete operations in the Gorton mill, the only difference between the two being the size of the cutter. The final cut is taken with a slightly larger cutter; since the final cut is relatively light, tool side loading is reduced, deflection is low and accuracy is high. As the Gorton mill is a mechanical cam controlled machine, the partially formed vane passages of the isothermal forging could not be utilized to effect a savings in machining time. However, no problems were experienced with intermittent machining cuts or abnormal tool wear. Solid carbide cutters are normally employed and will typically last 36 cycles before being resharpened. Cutters are purchased for finish cuts and will be resharpened once and used for roughing cuts.

The areas which failed to clean-up on machining the vane passages are illustrated in Figure 15. These areas were hand blended on impeller S/N 6 only so as to remove a minimum of 0.010 inches (0.25 mm) and clean up any remnants of surface contamination. Following final machining, this impeller was glass bead peened per AMS 2430 to an intensity of 3-5A_2 with 400 percent coverage. The impeller was subsequently anodized and is now in engine running condition. The anodize is used as a final inspection for alpha segregation.

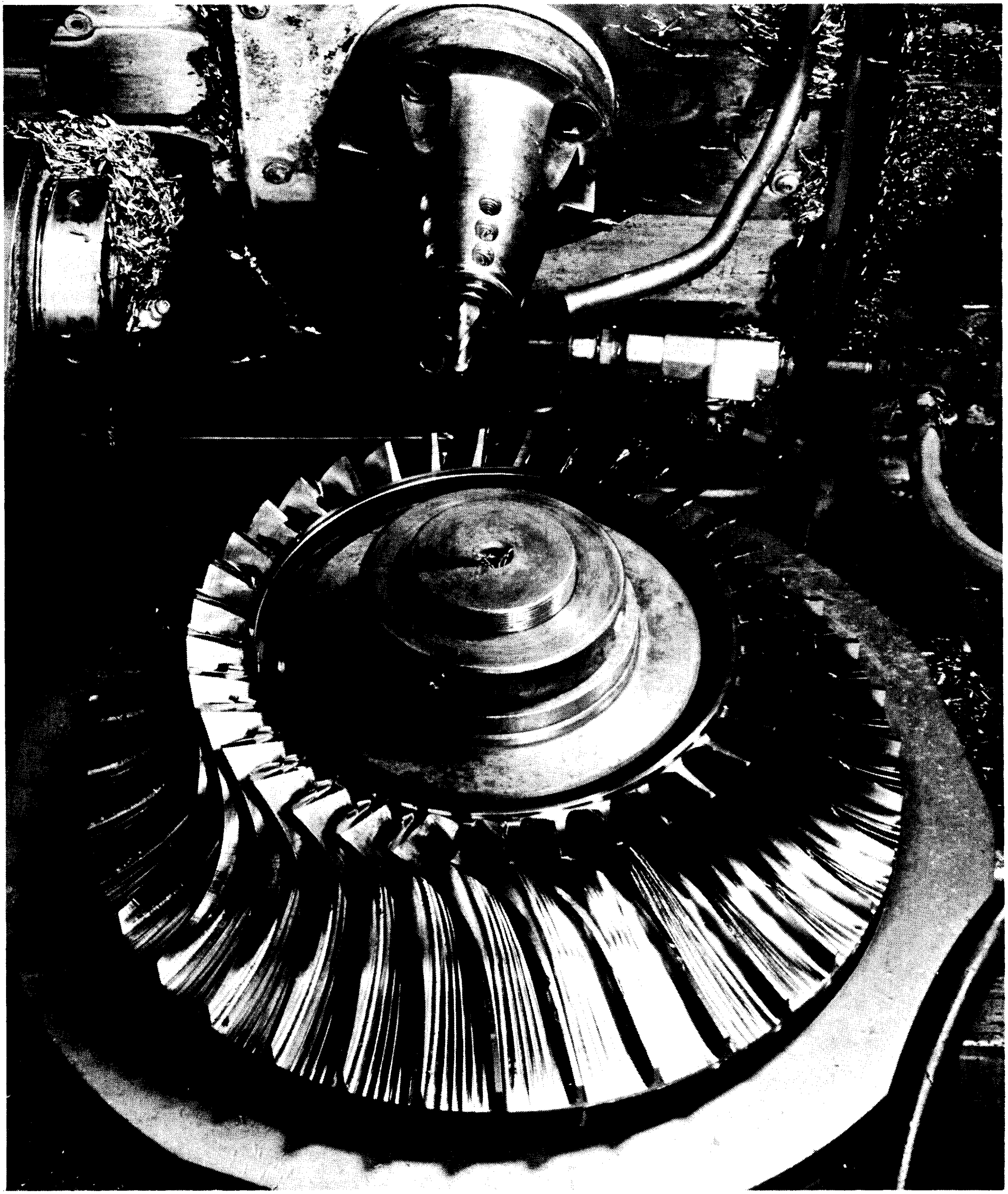
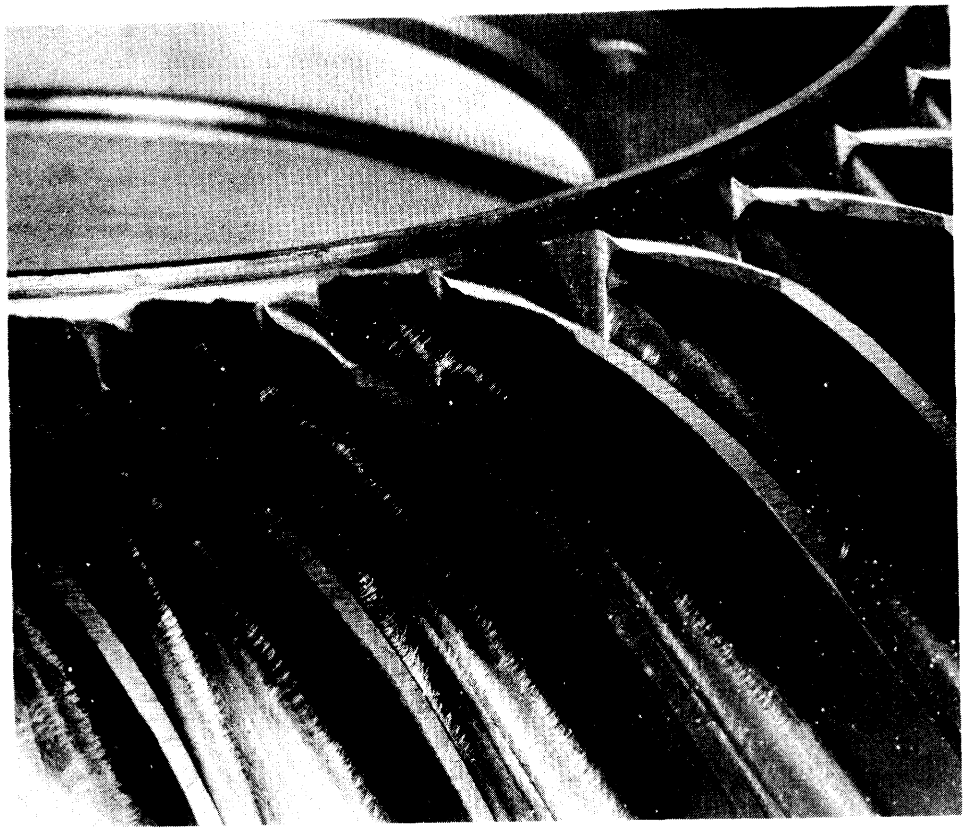


Figure 14. A T53 Impeller After Machining in a Gorton Mill



Mag. 1.25X

Figure 15. Area Which Failed to Clean-Up on Impeller S/N 6

4.0 COST ANALYSIS

One of the major objectives in this program was to determine the cost reduction potential of the isothermally forged impeller. It was previously noted that isothermal forging reduced the amount of metal to be removed by nominally 50 percent for a net savings in chips of about 13.5 lbs (6.12 kg). However, while conducting the cost analysis for this part, it became apparent that component design and the production tooling concept are very influential in determining the efficiency of metal removal. These factors as well as the influence of isothermal forging on other processing costs are discussed below.

4.1 Machining Costs

The T53 impeller was originally designed so that all vane sections were radial with respect to the axis of rotation. This configuration greatly simplifies the machine tool requirement and permits the use of a cam controlled machine with only three axes. The machining concept was developed by Lycoming and several high speed milling machines were engineered and built by Gorton. While these are only single spindle machines, it is standard practice for one operator to run an average of three machines. For the T53 impeller, the nominal cycle time is 4.8 hours with one rough machining cycle and one finish machining cycle required per part. This has resulted in a very efficient vane machining practice; the average cost of Gorton milling each impeller is only $130.17 (military selling price). This makes it difficult to significantly lower the cost of vane machining even if alternative machining practices were used which would more effectively utilize the partially forged vane passages of the isothermal forging. It was previously noted that the Gorton mill being a cam controlled machine could not compensate for the reduced volume of metal in the vane passage by shortening the machining time.

However, in an effort to further explore the cost reduction potential of isothermal forging, a cost analysis was conducted on the use of alternate machine tooling to generate the vane passages for the T53 impeller. For this analysis, numerical controlled (NC) milling and Gorton milling with adaptive control were considered as alternates to conventional Gorton milling. The results of this analysis, given in Appendix B, show that either of these alternatives can provide a significant reduction in the cost of machining as summarized below:

	Conventional Gorton	NC	Gorton With Adapt Control
Vane Milling Cost/Part	$130.17	$60.71	$91.10
Break-Even Point	--	7,630 Parts	5,948 Parts

From these data, it is apparent that the break even point is relatively high. These numbers exceed the anticipated production of 2849 units over the next eight years. This analysis confirms that for the T53 impeller the partially formed vane passages cannot be utilized effectively even with more advanced machining concepts. There are, however, other areas of weight reduction in the isothermal forging (approximately 6.6 lbs or 2.99 kg) that may be exploited for cost reduction purposes.

The process operations up to and including Gorton milling that are performed on the T53 impeller are listed in Table V. The rough machining operations through operation No. 40 are scheduled prior to heat treat so as to reduce the section thickness for solution treating. Since it was shown in this program that the section size of the isothermal forging was suitable for direct heat treatment, the forging can be purchased in the STA condition rather than in the mill annealed condition. This will allow the elimination of operation Nos. 50 through 80 and rescheduling the initial machining operations to be more efficient. Rough machining time will be reduced by a ratio that approximates the reduction of material volume. For a typical run of production parts, these cost savings per part are estimated to be as follows:

Rough Machining	-	$66.61
Heat Treat, Clean	-	4.40
Total Cost Savings	-	$71.01

It is obvious that this magnitude of cost reduction, which represents only about 5 percent of the total part cost, is not as substantial a number as might seem possible with a nominal 50 percent reduction in machining chips. However, it must be pointed out that for impeller designs which are more dictated by performance rather than by cost, the impact of isothermal forging on cost reduction could be much different. Machining costs escalate rapidly for high performance impellers with combinations of non-radial vane sections, a larger number of vanes, thinner vanes, or backward leaning vanes. Five axis machine tools and lighter machining cuts to avoid tool or part deflection would be required to accomodate the more intricate vane shape. In this case, the partially formed vane passages of an isothermal forging could be more influential in reducing vane machining costs than was possible for the T53 impeller.

4.2 Forging Costs

While the IITRI program successfully demonstrated the capability of isothermal forging, it may not be possible to determine truly representative forging costs until some reasonable production base is established. However, in an attempt

TABLE V

PARTIAL OPERATIONS LIST FOR T53 Ti6Al-4V IMPELLER

Operation No.	Operation Name	Remarks
01	Material preparation	
12	Turn OD	
22	Face, bore, form & groove	Inlet face & inlet side of bore
31	Face, bore, & form contour	Aft face & aft side of bore
40	Trace OD contour	Vane OD contour
46	Ultrasonic inspect	
50	Clean	
60	Solution treat	
70	Age	
80	Inspect hardness	
93	Face, bore, C'bore & chamfer	Inlet, ID, bolting flange
103	Finish groove, face, bore & chamfer	Aft face & bore
121	Grind ID and inspect	Aft bore
130	Grind ID, face & inspect	Bolting flange
142	Finish trace undercut	
153	Face trace & OD contour	
161	Drill, C'sink & tap	Bolting holes
173	Deburr holes	
186	Inspect	
192	Mill 36 blades	Gorton mill

to assess the impact of isothermal forging costs, the T53 impeller forging was reviewed in detail with Wyman-Gordon, Grafton, Massachusetts. Based on the results of this forging analysis and also on the above machining analysis for this part, several factors were defined as discussed in the following paragraphs.

4.2.1 Tooling

Tooling costs will be significantly reduced if the form and detail of the vane passage can be relaxed. As discussed in the machining study, machining costs are insensitive to the volume of metal removed from the vane passage for the T53 impeller. Therefore, it would be desired to achieve a partially formed vane passage that contributes to reducing input material costs but not to higher die costs. It was suggested by the forger that vane thickness and edge radii would have to be increased and the depth of the passage reduced to improve fill. The partially formed vane passages of the IITRI isothermal forging alone accounted for a calculated weight savings of 6.91 lbs (3.13 kg). It was estimated that between one-half to two-thirds of this weight savings could be retained without adversly impacting tooling or production costs.

4.2.2 Billet Stock

The IITRI program utilized hollow Ti-64 billet stock to produce the isothermal forgings evaluated in this program. The use of solid billet stock for future forgings is considered to be more cost effective due to higher material utilization. This will result in a solid web at the bolting flange of the finished forging which represents about 1.5 lbs (0.64 kg) of material. The hole in the hollow billet stock used in the IITRI evaluation represented approximately 15 lbs (6.8 kg) of material. Hollow PM preforms have the potential to be an excellent starting material for isothermal forging; however, as yet they have not been adequately demonstrated.

4.2.3 Heat Treat

Conventional forging practice requires the impeller to be heat treated only after rough machining has been accomplished. The lower mass of an isothermal forging will allow an adequate solution treatment to be obtained as was demonstrated in this program and discussed earlier. Therefore, this allows the forging vendor to perform the heat treatment on the as-forged part. Some cost savings are effected by this approach as one annealing treatment is eliminated and qualification testing is simplified.

4.2.4 Cost Summary

Based on implementing the above considerations, an engineering cost estimate was made for a slightly modified T53 isothermal forging. Using the anticipated production rates discussed previously, the per part and tooling costs are as follows:

Isothermal forging, each	\$550
Tooling	\$38,000

The isothermal forging cost is \$61 more than current conventional forging price of \$489. This results in a net cost savings of \$10.01 for each finished impeller when allowing for the \$71.01 cost savings due to machining as discussed in Paragraph 4.1. When the tooling cost are considered, the break-even point is obviously well in excess of the 2849 units anticipated over the next eight years.

5.0 CONCLUSIONS AND RECOMMENDATIONS

1. The quality and metallurgical characteristics of the isothermal forgings, including mechanical properties, were considered acceptable by comparison with conventional forging requirements.

2. A finished impeller was satisfactorily machined from one of the isothermal forgings with only minor evidence of under fill. This part is considered to be suitable for engine running.

3. The state-of-art on isothermal forging practices for production parts indicates that the increased cost of isothermal forging will be generally greater than cost savings due to reduced input material. Part of the cost savings in machining normally will be required to off-set the remainder of the increased cost of isothermal forging.

4. A cost analysis on the use of isothermal forging for the T53 impeller showed only nominal cost benefits primarily due to the already low machining costs for the conventionally forged and machined part.

5. Based on the above considerations, it is recommended that similar analyses be conducted on other titanium components where the ratio of rough machine costs to final part cost is high. It is further recommended that activity be funded to productionize isothermal forging for those components which can demonstrate a cost reduction.

REFERENCES

1. T. Watmough, "Development of Isothermal Forging of Titanium Centrifugal Compressor Impeller," Army Materials and Mechanics Research Center, Final Report No. AMMRC-CTR-73-19, May 1973.

APPENDIX A - DIMENSIONAL INSPECTION DATA

Forging S/N 5 was originally selected for dimensional inspection because it was the heaviest of the forgings and visually appeared to have the best die fill. Figure A-1 shows the dimensional checks that were made and Table A-I tabulates the data and compares it with the required dimensions on the final machined drawing. The two tabulated values given represent the range of measurements that were taken.

Depending on how the finished part was floated in the forging enevelop, the data indicated that some of the blade tips T6 would not clean up. This was found to be the case after the Gorton milling operation.

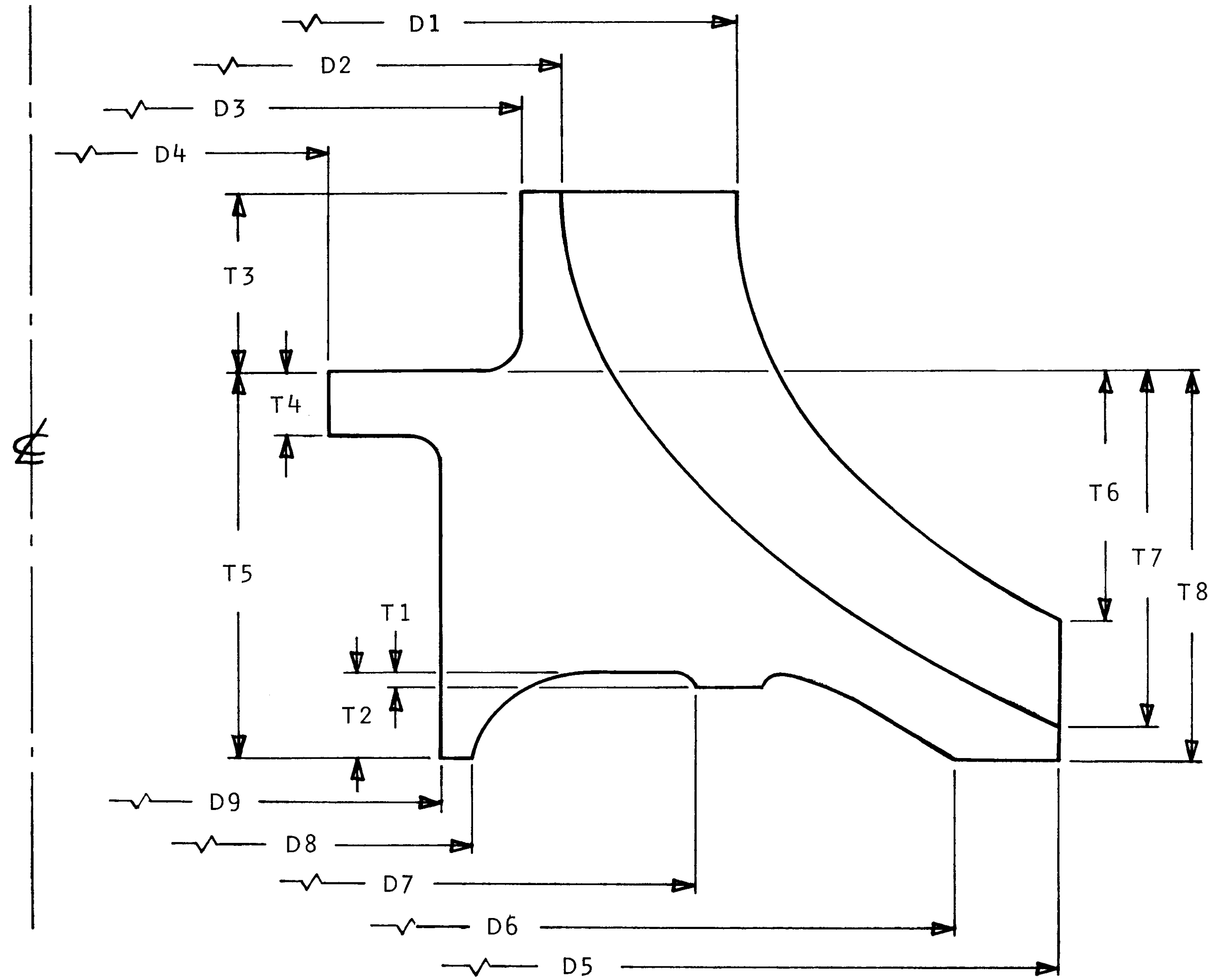


Figure A-1 Dimensional Checks Performed on Forging S/N 5

TABLE A-I

RESULTS OF DIMENSIONAL INSPECTION ON FORGING S/N 5

Dimension	Forging Measurements - Inches		Finish Machined Dimension - Inches
D1	9.482	9.475	9.250
D2	7.430	7.424	7.410
D3	7.055	7.065	7.22
D4	4.770	4.755	4.87
D5	13.264	13.251	13.05
D6	12.060	12.046	12.00
D7	9.039	9.020	9.00
D8	6.402	6.385	6.40
D9	6.051	6.040	6.20
T1	.095	.088	0.10
T2	.481	.513	0.47
T3	1.080	1.066	1.061
T4	.325	.326	0.200
T5	2.212	2.240	2.102
T6	1.657*	1.484	1.526
T7	2.047	2.065	
T8	2.234	2.244	2.102

*Undersize

APPENDIX B - ALTERNATE VANE MACHINING PRACTICES

The partially formed vane passages of the isothermally forged impeller account for slightly over half of the nominal 13.5 lb (6.12 kg) weight difference compared to the conventional forging. Current machining practice (Gorton mill) removes a total of 64.8 in^3 (1,062 cm^3) whereas the isothermal forging requires that only 21.6 in^3 (354 cm^3) be removed. The difference is equivalent to 6.91 lbs (3.13 kg) less metal that must be machined away.

Unfortunately, the Gorton mill is unable to compensate for this reduced amount of metal. The cam controlled mechanism moves the milling cutter on prescribed paths along the entire length of the vane passage whether or not there is metal present to be removed. Two alternate machining techniques were reviewed, therefore, to determine their ability to compensate for the lower volumn of metal and, hence, improve overall machining efficiency. In each case, it is assumed that the machines are set-up and dedicated solely to the production of T53 impellers, and that the level of operator surveillance (parts per operator) is the same as current practice.

Numerical Control - NC milling would reduce the actual machining time by programming vane passage cuts only where metal existed to be removed. A single, three-spindle NC mill can replace five to six Gorton mills on a capacity basis and meet anticipated production requirements for the T53 impeller.

The following analysis shows potential savings per part and the break-even point based on capital investment:

a)	Cost of Gorton milling per part	$	130.17
b)	Reduced volume of isothermal Forged vane passage $\frac{(64.8-21.6)}{64.8} \times 100$		66.7%
c)	Machine efficiency factor [1]		80.0%
d)	Potential cost savings per part (130.17) (.667) (.80)	$	69.46
e)	Total vane machining cost (130.17-69.46)	$	60.71
f)	Capital investment	$	500,000
g)	Chargeable costs for (8) years [2]	$	530,000
h)	Break-even point $\frac{\$530,000}{69.46}$		7,630 Parts

[1] Estimated efficiency with which machine will compensate for volume of void in vane passage.

[2] Based on (20) year tool life plus investment charges at 10 percent per year for first (8) years which is assumed to be the remaining production life for T53 impellers.

Adaptive Control - The addition of adaptive control to the Gorton mill will reduce machining time by increasing the travel rate when no metal is being removed. The cutting tool power requirement is monitored electronically and the travel rate is controlled as an inverse function of the power requirement. The machine efficiency factor as defined above will be lower than NC milling as the whole travel path will still have to be traversed, but it can now do so at a faster rate. It is anticipated that four Gorton mills with adaptive control can similarly replace five to six conventional Gorton mills on a capacity basis and meet anticipated production requirements.

A similar analysis on modifying the Gorton Mill with adaptive control is given as follows:

a)	Cost of Gorton milling per part	$	130.17
b)	Reduce volume of isothermal Forged vane passage $\frac{(64.8-21.6)}{64.8} \times 100$..		66.7%
c)	Machine efficiency factor..................................		45.0%
d)	Potential cost savings per part (130.17) (.667) (.45)........	$	39.07
e)	Total vane machining cost (130.17 -39.07)	$	91.10
f)	Capital investment	$	140,000
g)	Chargeable costs for (8) years	$	232,400
h)	Break-even point $\frac{232,400}{39.07}$		5,948 Parts

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